System Characteristics of a Computer Controller for Use in the Process Industries

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INTRODUCTION

BEFORE the detailed design of a computer may be begun, it is necessary to set up some fairly detailed specifications which define the operating characteristics of the proposed system. It is the purpose of this paper to show how these specifications were developed for the RW-300 digital-control computer, the first computer designed specifically for process control. The specifications for this computer were developed as a result of a number of studies carried out on specified industrial processes over a period of almost three years.

THE PROCESS CONTROL PROBLEM

The functional and environmental specifications for a digital system arise explicitly or implicitly in answer to a number of questions which can be raised about the job the system is to perform. The job to be done by a process-control computer is that of making adjustments in process variables to attain some specified process objective in the face of variations (in raw material characteristics, ambient conditions, etc.) over which no control can be exercised. In the course of answering questions about the process-control jobs we will show how the basic specifications for the RW-300 were developed. A description of the computer will complete this paper.

Inputs

What is the source of the information, and how may it best be translated into the language of the machine? The data entered into a process-control computer is fundamentally of two different kinds: data from process instruments (measuring temperature, flow, pressure, liquid level, chemical composition, viscosity, density, etc.), and data supplied by the operator as requests for special operations from the system, or as changes to be made in system operation. The instrument data is fundamentally analog in character, normally in the form of an electric or a pneumatic signal. The signal may continuously represent the quantity being measured by the instrument (as a thermocouple voltage continuously represents the temperature), or it may represent the physical quantity being measured only at intervals (as the output of a chromatograph represents a composition by a peak voltage or by the integral of a slowly varying voltage). In addition to these analog instrument signals, there may be digital signals designating the mode of operation of the instrument.

Although the analog input information could be transcribed manually by an operator and inserted into the computer control system in digital form, this would be an inconvenient slow operation, subject to human errors of transcription.

The digital information inserted by the operator is most conventiently presented in decimal form, so that the operator can prepare it easily. However, it may be desirable to permit the operator to initiate special requests and changes by pressing a button or operating a switch.

What kind of information must be represented, numerical or alphabetic? As can be inferred from the answer to the first question, the information read into the computer is fundamentally numerical in nature. The precision of the input data is limited by instrument precision. A precision of better than 1 per cent of full scale is unusual in common process instruments.

What is the rate of flow of information from the source? Data from the continuous type instruments are available at any time. From instruments like the chromatograph, data is available only periodically. Typically, a chromatograph signal might be sampled periodically every ten seconds over a period of five or ten minutes. Although part of the instrument data is available continuously, the variation in process variables is usually slow enough that the computer control system need to sample the instruments no oftener than once every five minutes or so. The number of instruments which must be so sampled varies from process to process and from problem to problem. A typical complex process may require as few as 25 inputs or as many as 250 inputs.

Data Processing

What must be done to the information? Must it be altered; if so, how? A process-control computer must be able to handle many different kinds of computations and manipulations of process input data. Typical of the kinds of data processing required are data interpretation, calculations for optimal control, data logging or printout of process information, and checks for hazardous process conditions or for instrument failures. By *interpretation of data* we mean the translation of readings from process instruments into numbers corresponding to the physical quantities these readings represent. This interpretation may be as simple as the application of a scale factor. It may include a linearizing operation like one which must be applied to a thermocouple to translate voltage into a temperature. Or it may require the solution of a set of simultaneous linear algebraic equations, as are required to

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compensate for interferences between a number of chemical compounds analyzed by a mass spectrometer. The *calculations required for control* in general require the solution of very nonlinear algebraic equations. These equations vary widely from process to process, and there seem to be no characteristics common to all of them. The *data-logging* operation requires that information be printed out in a digital-decimal form. The *checking of process instruments* and process conditions for malfunctions requires in general the comparison of observed or calculated data with certain standard values established by the operator. These comparisons and the decisions based on these comparisons comprise the checking operation.

How much time is available for processing the information? The data interpretation and control calculations need to be carried out at a frequency determined by the dynamics of the process and by the rate at which significant changes take place if the variables are slow and the time constants involved in a process are fairly long. A control calculation once every five minutes to once every hour or half hour is sufficient for most processes. The data-logging calculation may also vary depending on the state of the process and the desires of the operator. A complete logging operation of all process variables and related data once every five minutes is most frequently required. The alarm-checking operation may again be one which should be carried out very frequently or relatively infrequently depending on the variable in question. Some process checks must be done once a second; others can be carried out as infrequently as once every fifteen minutes to an hour.

Outputs

What must be the output rate of the process information? The rate at which output adjustments are made on the process is again a function of the dynamics of the process and the rate of change of the uncontrollable variables. In most processes an adjustment once every fifteen minutes to a half hour is ideal. In some processes more frequent or less frequent adjustments may be desirable.

What is the purpose of the output information? What form should it be in to accomplish this purpose most effectively? There are two principal forms of output information, just as there are two forms of input information. The first is data calculated by the computer which must be used to adjust process variables. The second is data in fundamentally digital form which must be supplied to the operator. The data supplied to the process may itself be of two forms. It may be necessary for the computer to send a digital, on-off signal to turn an instrument on or to effect some calibration or to open or shut some valve; it will be necessary to make adjustments in instrument settings by means of analog signals which correspond to digital numbers calculated by the computer as the proper setting for the instruments. Added to this is the more conventional digital output system required for data-logging purposes. As was mentioned before, this requires decimal output data. Typically, the number of process outputs is *at most* about half the number of inputs.

Reliability and Maintenance

What effect would a machine error have on the information flow, and how would it affect the operation being performed? May the operation be interrupted for emergencies or for regular periods of preventive maintenance? Conventional instruments used in the process industries are typically very reliable. Operation over periods of several years without preventive maintenance and without failure is not uncommon. However, every process instrument has some probability of failure, and the process engineer, in designing a control system, takes this into account and assures that the control system is fail-safe, that is, that a failure of some instrument or even some combination of instruments will not result in a disaster. A digital-control computer, by its very complexity, is not likely to be as trouble free as conventional and very simple pneumatic instruments. However, as might be expected in view of the fail-safe precautions commonly taken, the problem involved in incorporating a digital-control system into a process is different in degree rather than in kind from the problem of installing the conventional instrumentation. The entire control system must still be fail-safe, regardless of the reliability of the computer.

Nevertheless, the practical effectiveness of a control system of this kind is very much dependent upon its reliability, and upon the ease with which it is repaired when failures do occur. High reliability and great ease of maintenance are very important. In addition, it must remain practical to do preventive maintenance with the least possible interference with normal computer operation.

Environment

What are the environmental conditions under which the system must operate, and what effect should these have on the system characteristics? Environmental conditions for computer control systems in process industries can be expected to vary widely from installation to installation and to be very difficult. Wide temperature variations, from below freezing to somewhat above 100°F, are frequently encountered as are wide variations in humidity. Corrosive gases and vapors of one kind or another are often present in the air. Large quantities of dust are not at all unusual. Vibration due to the proximity of heavy machinery can be anticipated. Electrical power supplied to the computer may be locally generated, with the result that line voltages and frequencies change by 10 or 20 per cent of their nominal values. And it can be expected that computer use and maintenance will be in the hands of inexperienced operators who are unimpressed by delicate or fragile equipment.

SYSTEM SPECIFICATIONS

The answers to the above questions resulted in a set of rough system characteristics which served to guide the designers when detailed decisions were made about the computer's operation. These system specifications may be stated very briefly as follows.

Because of the complexity and variety of the problems to be handled by a process-control computer, and because of the importance of flexibility in these applications, the basic machine should be a stored-program computer. The computer should have available a very large memory for storage of programs of instructions. The important requirement that the system be fail-safe suggests that the computer outputs, used to adjust process variables, be employed with conventional process controllers which compensate for the second-by-second variabilities in process conditions. The computer itself therefore need be of only moderate speed.

An input-output system capable of handling some 250 analog inputs, 100 analog outputs, and a similar number of one-bit inputs and outputs is necessary. In order that the process input-output system be suitably matched to computer speed and to typical process dynamics, all inputs should be made available to the computer and all outputs adjusted by the computer at least once a minute.

A conventional decimal input-output system is also required, but since it is not necessary to read in or print out large volumes of data, relatively low-speed devices are satisfactory.

Because of the inherent lack of precision in instrument input and output equipment, it might appear that the great precision obtainable from a digital computer would be unused in process control applications. It is certainly true that the ten-decimal-digit word length useful in some scientific computations is not required here. However, a computer precision somewhat greater than that supplied by the instruments is very desirable to make scaling problems easy for the programmer. An input conversion system accurate to one part in 256 or 512 (8 or 9 bits) would be adequate, and a word length two or three times that is appropriate. Since most of the computer's operations do not require human intervention, the binary number system is suggested, with decimal output and input conversions handled by the computer when necessary.

The reliability and environmental specifications emphasize the importance of mechanical and electrical ruggedness and ease of maintenance.

DETAILED CHARACTERISTICS

The RW-300 computer controller is designed to fulfill all of the requirements above as economically as possible. Its detailed characteristics were worked out by planning a hypothetical computer, putting it into typical industrial process-control systems, and then evolving a more detailed set of specifications while altering the computer's characteristics to meet new demands. This whole operation was carried out, of course, with still another objective in mind: that of providing an ultimate system which would be cheap enough to permit reasonable payoff periods in these applications.

The result, which will be described in the following sections in some more detail, is a transistorized (for reliability) general purpose, stored-program digital computer. It has a magnetic drum memory (for large capacity at low cost operable over wide temperature variations) and operates in a serial mode with fixed-length binary words. It contains analog and digital input and output facilities, the number of which can be increased or decreased without affecting the internal logic of the basic computer.

The computer uses an 18-bit binary word for numbers, consisting of a sign bit and 17 magnitude bits. The magnitude of each number is less than one. This word length is approximately twice the word length of the analog-to-digital and digital-to-analog conversions and is compatible with the accuracy of industrial instrumentation. An infrequent number of cases arises in process control requiring the use of double-precision arithmetic operations. Because of their infrequent occurrence it was not necessary to provide automatic double precision. These operations can be programmed through the use of the other instructions in the machine's repertoire. The instruction system contains 19 instructions of the one plus one address type. That is, each instruction specifies the address of one operand and the address of the next instruction to be executed. Instructions are stored in the magnetic drum memory as two adjacent words. Thus, 36 bits are used to store an instruction. The first word of an instruction pair contains the operand address and the execution time of the particular operation. The second word contains the next instruction address and the instruction code. The execution time field gives the programmer the capability of specifying the number of bits used in the multiplication, division, shifting, and digital-input instructions. These 19 instruction codes can be divided into three categories. The first category contains the basic arithmetic operations of add, subtract, multiply, and divide. The second group contains the conditional transfer or program-branching type of operations. These are transfer on a zero number, transfer on a negative number, transfer on overflow, and compare magnitude. The stop instruction is also put in this category. The third category of instructions contains the data handling operations for loading and storing either of the two principal arithmetic registers, transferring information between these two registers, shifting of numbers in the registers, merging and extracting numbers (logical add and multiply), and the digital input-output instruction.

The time required for execution of the various instructions is as follows. This includes reading the instruction from memory, obtaining the operand, and completing the operation where a minimum access time is allowed for obtaining both the instruction and the operand.

Add and subtract	0.91 milliseconds
Multiply	2.99 milliseconds
Divide	2.99 milliseconds
Branch	0.65 milliseconds
Load	0.65 milliseconds
Store	0.78 milliseconds.

These speeds of operation and the command repertoire are compatible with data-processing requirements and information-flow rates encountered in process-control systems.

The internal structure of the RW-300 can be divided into the following operational units: a magnetic drum memory, a control unit, an arithmetic unit, a digital input-output unit, an analog input-output unit, a test and maintenance panel, and an operator's control panel.

Memory

The addressable memory consists of 64 tracks of 128 words each. One of these tracks is reserved for a memory-loading program which will load the memory from punched paper tape. This track is unalterable by the programmer as a safety precaution. A second track of the 64 is used for a 16-word circulating register for fast access. The remaining 62 tracks of 7936 words are used for general storage. It is possible to write into only eight of these tracks at a time under computer control, thus giving 1024 words of variable storage in addition to the circulating register. The eight tracks are selected by means of an accessible connector plug between the writing circuits and the memory unit. The normally used 8 tracks have both a reading and a writing head which are separated by 32 words such that a number may be read from a track, operated upon, and stored back into its original address without waiting an entire drum revolution. The memory capacity for program constants and variable storage was determined on the basis of programming several typical industrial processes. Additional memory capacity was added over and above that determined in the study process since additional use of the computer once installed in a process will surely be made, thus requiring greater storage capacity for both program and constants.

Control Unit

The control unit of the computer consists of registers and counters to store information concerning the instruction and the sequence of steps in the execution of the instruction. Two circulating registers on the magnetic drum are used to store the operand address and next instruction address. The track selection portions of these addresses are transferred to a selection register at the proper time. Sector address coincidence is determined by serially comparing the sector address portions of the instruction to a sector-identification track on the drum. A third circulating register on the drum is time shared with the arithmetic unit but is used to store the execution time of an instruction when used in the control unit. A second flip-flop register is used to store the actual instruction code. Two flip-flop counters are used to distinguish the digit times in a word time and to sequence the steps involved in executing an instruction.

Arithmetic Unit

The arithmetic unit of the computer consists of two main circulating registers, the time-shared register mentioned above, and an adder. The principal arithmetic register contains the results of instructions and holds one of the operands in the majority of instructions. The second arithmetic register is used to hold the multiplier and remainder for multiplication and division. Because the contents of the second register are readily interchanged with the principal arithmetic register, it can be used as a one word time, fast access, temporary storage. The time-shared register is used for multiplication and division. It is not addressable.

Digital Input-Output Unit

The digital input-output unit contains the basic facilities for reading in 6 bits from a paper-tape reader and for putting out 6 bits for a paper-tape punch and/or typewriter. A large number of digital inputs and outputs other than the paper tape and print inputs and outputs is possible without changing the basic computer. The total number of addresses available for digital input or output devices is 64 and the maximum word length for these inputs and outputs is 18 bits. These digital input-output facilities are more than adequate for the alarm output and operator input instructions encountered in process control.

Analog Input-Output Unit

The analog input-output system does not require programmed control from the computer. All analog-input quantities are converted to a digital number and stored in specific addresses in the memory. All analog outputs are read automatically from the memory and converted to analog quantities for control. Input quantities are obtained from the memory by the computer as are any other numbers stored in the memory. The number of analog inputs and outputs required for process control varies considerably between applications. The maximum number of inputs could be as high as 512, and the number of outputs could be as high as 256. Changes in the number of analog inputs and outputs used does not change the basic computer. The input-output system is a cyclic system in that all inputs and all outputs are read during a fixed length of time and then the cycle is repeated. This makes the latest information available to the computer at any time where the maximum delay in an input is a matter of a few seconds. Ten binary digits are used in converting analog-to-digital and digital-to-analog. The basic full-scale analog inputs fall into two categories. These are low-level signal inputs and high-level signal inputs. The standard low-level input is 0 to 10 millivolts while the higher-level inputs are standardized at 0 to 10 volts. The latter may be obtained from instruments which have current outputs sufficient to give 0 to 10 volts full scale. The analog outputs are standardized at 0 to 5 milliamperes, although higher current or voltage outputs can be specified without loss in accuracy. A single converter is time shared for all analog inputs and all analog outputs, and switching of inputs and outputs is done both with relays and electronic switches.

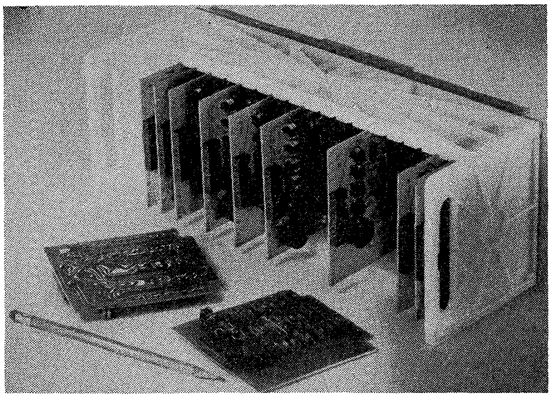

Fig. 1—Computer module and insert cards.

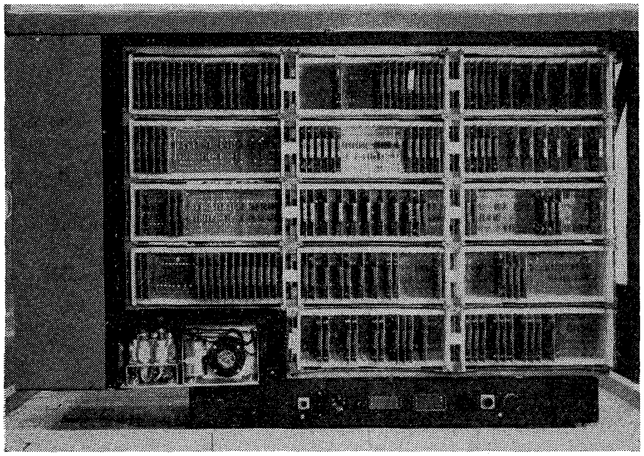

Fig. 3—Computer subframe holding 14 modules.

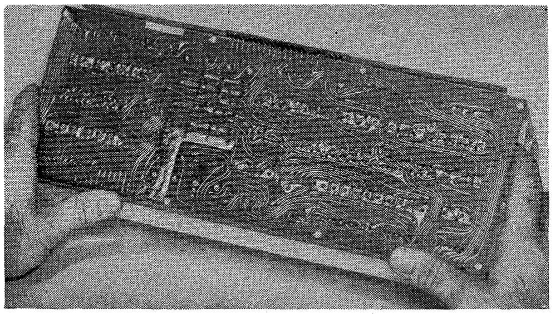

Fig. 2—Module bottom etched wiring.

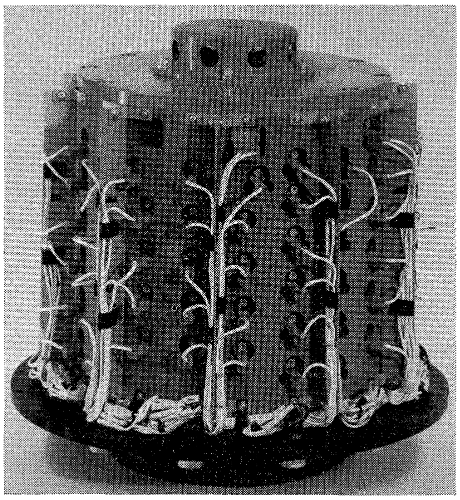

Fig. 4—Magnetic drum memory (cover removed).

Test and Maintenance Panel

The test and maintenance panel contains the facilities for code checking of programs, marginal testing, and for on-line trouble shooting of the machine. The normal automatic sequence in executing an instruction is to first obtain the instruction from the memory, then to obtain the operand, and finally to perform the indicated operation. It is possible to interrupt this sequence of operations from the test and maintenance panel and to do these operations in two steps at a manually controlled rate. The first step, under the control of the operator, picks up the instruction from the memory address and through the aid of a built-in oscilloscope the operator may inspect the address of the operand, the address of the next instruction, the instruction to be performed, and the execution time. A second step permits the computer to pick up the operand and to perform the indicated operation. The operator may inspect the results of the operation and note any changes in the next instruction address. The oscilloscope also allows the operator to look at the contents of the arithmetic registers and other important logical points in the computer. Neon lights are also provided which indicate the contents of the control registers and certain designated flip-flops.

Controls to adjust the computer voltages and clock-pulse amplitude for marginal checking are located on the maintenance panel. Digital input switches on the test and maintenance panel can be used for program checking (break-point switches) so that portions of programs may be checked without running through the entire program.

Operator's Control Panel

The operator's control panel contains the push buttons and indicating lights to start the computer, to stop the computer, to turn the power on and off, to resume at the point of stopping in the program, and to load the memory from punched paper tape.

The high reliability, ease and speed of maintenance, and environmental immunity specifications are by far the most important requirements for any process-control computer. RW-300 reliability is achieved by using only high quality components, maintaining rigid quality control on the use of these components, and derating all components a considerable amount. Conservative circuit-design techniques with wide tolerances, for component variation, load variation, and voltage variation, are used throughout. The RW-300 computer is almost entirely transistorized. Both germanium and silicon diodes and transistors are used in the machine.